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Non-Tidal Wetlands

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EXECUTIVE SUMMARY

Although there are many different systems for defining and classifying wetlands, for this chapter we define wetlands generally as areas of land where the water table is at or near the surface for some defined period of time, leading to unique physiochemical and biological processes and conditions characteristic of waterlogged systems. Wetlands exist in both inland and coastal areas, covering approximately 4–6% of the Earth's land surface. They are found on every continent except Antarctica and in every climate from the tropics to the tundra. This chapter examines the possible impacts of climate change on non-tidal (primarily inland) freshwater wetlands.

Wetlands have many functions that have socioeconomic benefits: They provide refuge and breeding ground for many species, including commercially valuable ones; they are areas of high biodiversity; they control floods and droughts and improve water quality; and they are used for recreation and education. The direct economic value of these benefits varies between regions.

Human activities—such as the conversion of wetlands to agricultural and forest lands, construction of dams and embankments, and peat mining—already pose a serious threat to wetlands worldwide. Mainly as a result of these activities, it is estimated that more than half of the world's wetlands have disappeared during the last century. These anthropogenic effects are most notable in densely populated areas and are expected to increase, especially in developing countries.

We are highly confident that climate change will have its greatest effect on wetlands by altering their hydrologic regimes. Any alterations of these regimes will influence biological, biogeochemical, and hydrological functions in wetland ecosystems, thereby affecting the socioeconomic benefits of wetlands that are valued by humans. Due to the heterogeneity of non-tidal wetlands, and because their hydrologic conditions vary greatly within and among different wetland types and sites, the impacts of climate change on these ecosystems will be site-specific. Impacts can be generalized for specific wetland types and, to some degree, wetland regions. However, generalization across wetland types is difficult and cannot be made in terms of locations or wetland categories.

We are highly confident that hydrologic changes or other disturbances that change the vegetation types in wetland areas will affect other wetland functions as well. However, many wetlands have inherently high spatial and temporal variability in plant communities due to climatic variations (e.g., seasonal flooding or drought) and variations in microtopography. We are confident that in some wetlands a changed plant community as a result of climate change will resemble at least some component of the existing community.

We are highly confident that climate change will affect the cycling of carbon in wetlands: Some carbon-sequestering wetlands will change from CO_2 sinks to sources due to a lowering of the water table or increased temperature. Changes in the source/sink relationship of wetlands have already occurred in parts of the arctic region. Climate change leading to an alteration in the degree of saturation and flooding of wetlands would affect both the magnitude and the timing of CH_4 emissions. Drying of northern wetlands could lead to declines in CH_4 emissions.

We are confident that climate change will affect the areal extent and distribution of wetlands, although at present it is not possible to estimate future areal size and distribution of wetlands from climate-change scenarios. Regional studies from east China, the United States, and southern Europe indicate that the area of wetlands will decrease if the climate becomes warmer. Climate warming also would have severe impacts on wetlands in arctic and subarctic regions in this respect because it would result in a melting of permafrost, which is the key factor in maintaining high water tables in these ecosystems.

Adaptation, conservation, and restoration of wetlands in response to climate change varies among wetland types and the specific function being considered. For regional and global functions (e.g., trace-gas fluxes and carbon storage), there are no human responses that can be applied at the scale necessary. For wetland functions that are local in scale (habitat value, pollution trapping, and to some degree flood control), possibilities exist for adaptation, creation, and restoration. However, wetland creation and restoration technologies are just developing, and we do not yet have reliable techniques to create wetlands for many specific purposes.

6.1. Introduction

6.1.1. *Aims and Goals of the Chapter*

This chapter examines the potential impacts of climate change on non-tidal wetland ecosystems and the possible options for responding to these changes. Tidal wetlands are covered in Chapter 9.

This chapter gives particular emphasis to the possible impacts of climate change on the areal extent, distribution, and functions of non-tidal wetlands, in the context of other natural or anthropogenic stressors that are likely to affect these ecosystems simultaneously. In addition to describing the importance of different climate variables and the range of factors that determine the sensitivity of individual wetlands, the chapter uses four case studies to illustrate the effects of climate change on certain defined wetland areas: the Sahel, northern boreal wetlands, Kalimantan (Indonesia), and the Florida Everglades.

This is the first time that IPCC has attempted a detailed assessment of the potential impacts of climate change on the structure and function of wetlands. Previous assessments briefly touched upon wetlands in a qualitative discussion of methane (CH_4) sources and sinks (Melillo *et al*., 1990) and discussed wetlands in the context of ecosystem responses to increased CO_2 concentrations, illustrated by case studies of the arctic tundra and a salt marsh.

The present assessment is hindered because the literature on wetlands is highly variable in quality and coverage and large gaps in knowledge remain regarding many of their regulating processes. In particular, relatively few studies exist on the impacts of climate change on inland wetlands; most that do exist have been carried out on specific wetland sites and/or have tended to focus on the Northern Hemisphere. These factors are reflected in the examples and conclusions in this chapter and in the emphasis on case studies. Recently, wetlands and wetland-related topics have begun to receive increasingly greater attention, and new information is expected to be published in the near future.

6.1.2. *Definition*

Wetlands exist in both inland and coastal areas, covering approximately 4–6% of the Earth's land surface. A wide variety of wetland definitions are found in the literature. Cowardin *et al*. (1979) argue that there is no single, correct, indisputable, ecologically sound definition for wetlands, primarily because of the diversity of wetlands and because the demarcation between dry and wet environments lies along a continuum. In general, a wetland describes any area of land where the water table is at or near the surface for some defined period of time, leading to unique physiochemical and biological processes and conditions characteristic of shallowly flooded systems (Mitsch and Gosselink, 1993). This chapter will discuss both permanent and temporary wetlands.

6.1.3. *Classification*

Wetlands usually are categorized according to their characteristic vegetation; their location (coastal or inland); the salinity of the water they contain; or other biological, chemical, hydrological, and geographical features. Coastal wetlands are influenced by the ebb and flow of tides and may include tidal salt marshes, tidal freshwater marshes, and mangrove swamps (see Chapter 9).

This chapter covers inland wetlands, or those not subject to tidal influences—including peatlands, swamps, marshes, and floodplains. Peatlands consist of bogs and fens, which may be forested, and are peat-accumulating wetlands in moist climates (peat is partially decomposed plant material). Bogs are acidic, poor in nutrients, and receive water from precipitation only, whereas fens are generally circumneutral, richer in nutrients, and receive water primarily from overland flow and/or groundwater. Swamps or forested wetlands are areas with little or no peat accumulation. Marshes or herbaceous wetlands and floodplains are flooded areas along rivers or lakes (Zoltai and Pollet, 1983).

More than seventy global classification schemes exist internationally. Because the response of wetlands to climate change tends to be site- or region-specific, no existing scheme is useful for this chapter in relating geographic or physical features with climate responses. For this reason, this chapter will focus on describing the climate and other variables that determine the response of individual wetland sites, rather than attempting to correlate responses with particular wetland types.

Many studies have shown that hydrologic parameters are strong controllers of wetland ecosystem structure and function (Gosselink and Turner, 1978; Novitzki, 1989; Kangas, 1990). The source, renewal rate, and timing of the water regime directly control the spatial and temporal heterogeneity of wetland ecosystem structure and function. The hydroperiod—defined as the depth, frequency, duration, and season of flooding—is usually the single most important regulator in wetlands, controlling many of their important characteristics (Lugo *et al*., 1990a). The hydroperiod is determined by the climate, topography, catchment area, soils, and geology of the region in which the wetland is situated (Armentano, 1990).

For this assessment, we focus on climate-change effects on hydrology as an integrative tool for our analysis. However, these effects are highly site-specific, and there are few general, categorical conclusions that can be drawn. There is extreme hydrological variation between and even within individual wetlands, such as differences in the direction of water flow (vertical, unidirectional, or bidirectional; Lugo *et al*., 1990b). This variability, coupled with the resolution at which these hydrological differences can be found, reinforces the need to describe wetland responses on a site-by-site basis. It is possible to generalize impacts for specific wetland types and, to some degree, wetland regions, but it is difficult to generalize across different wetland types.

6.1.4. Global Distribution of Wetlands

Wetlands are found on every continent except Antarctica and in every climate from the tropics to the tundra (Mitsch and Wu, 1995; Mitsch and Gosselink, 1993). Matthews and Fung (1987) recently conducted extensive surveys to determine the distribution of wetlands on a global scale and estimate that wetlands account for an area of 5.3×10^6 km^2, or approximately 4% of the Earth's land surface (Figures 6-1 and 6-2). This estimate is similar to other recent estimates (e.g., Aselmann and Crutzen, 1989) but indicates a possible reduction from previous estimates of around 6% (Bazilivich *et al*, 1971; Maltby and Turner, 1983). However, any estimate of global coverage will depend significantly on the definition of a wetland that is used.

6.1.5. Current Wetland Stressors

Wetlands already are threatened by a range of environmental factors, which can be natural or anthropogenic. It is estimated that more than half of the world's wetlands have disappeared since 1900. In the lower 48 states of the United States, approximately 53% of the original wetland area has been lost; 87% of this loss is attributed to agricultural development, 8% to urban development, and 5% to other conversions (Maltby, 1986). The same is valid for most of the developed regions of the world. The status of wetlands in developing countries is currently unknown to a large extent, but population pressures in many regions are steadily increasing the demand for food (Dugan, 1988), which can lead to wetland loss due to agricultural development. Many wetlands, especially in tropical regions, have so far escaped the impacts of human activities owing to their remoteness and unsuitability for agriculture (see Section 6.5.4). However, in recent decades, population pressures and technological advances have extended human influences into previously undisturbed areas (Armentano, 1990). For example, in 1989 it was calculated that only 82% of Indonesia's peat swamp forests remained in their original condition (Silvius, 1989); for some provinces (e.g., South Sumatra), it is predicted that no swamp forest will be left by the year 2000 (PHPA and AWB, 1990). Table 6-1 summarizes the main causes of present-day wetland loss.

6.2. Global Importance of Wetlands

Wetlands have many functions that are considered to have socioeconomic value: They provide refuge and breeding ground for many species, including commercially valuable furbearers, waterfowl, and timber; they often contain a high diversity of species; they control floods and droughts and improve water quality; and they can be used for recreation and education. The socioeconomic value of wetlands will vary from region to region, depending on which wetland functions the local economies regard as valuable. Table 6-2 identifies wetland types with their values.

Some wetlands (usually peatlands) contain potential energy for human consumption. In developing countries with shortages of energy and fuel, peat harvesting can be an attractive financial proposition if extensive peat deposits are available. This can

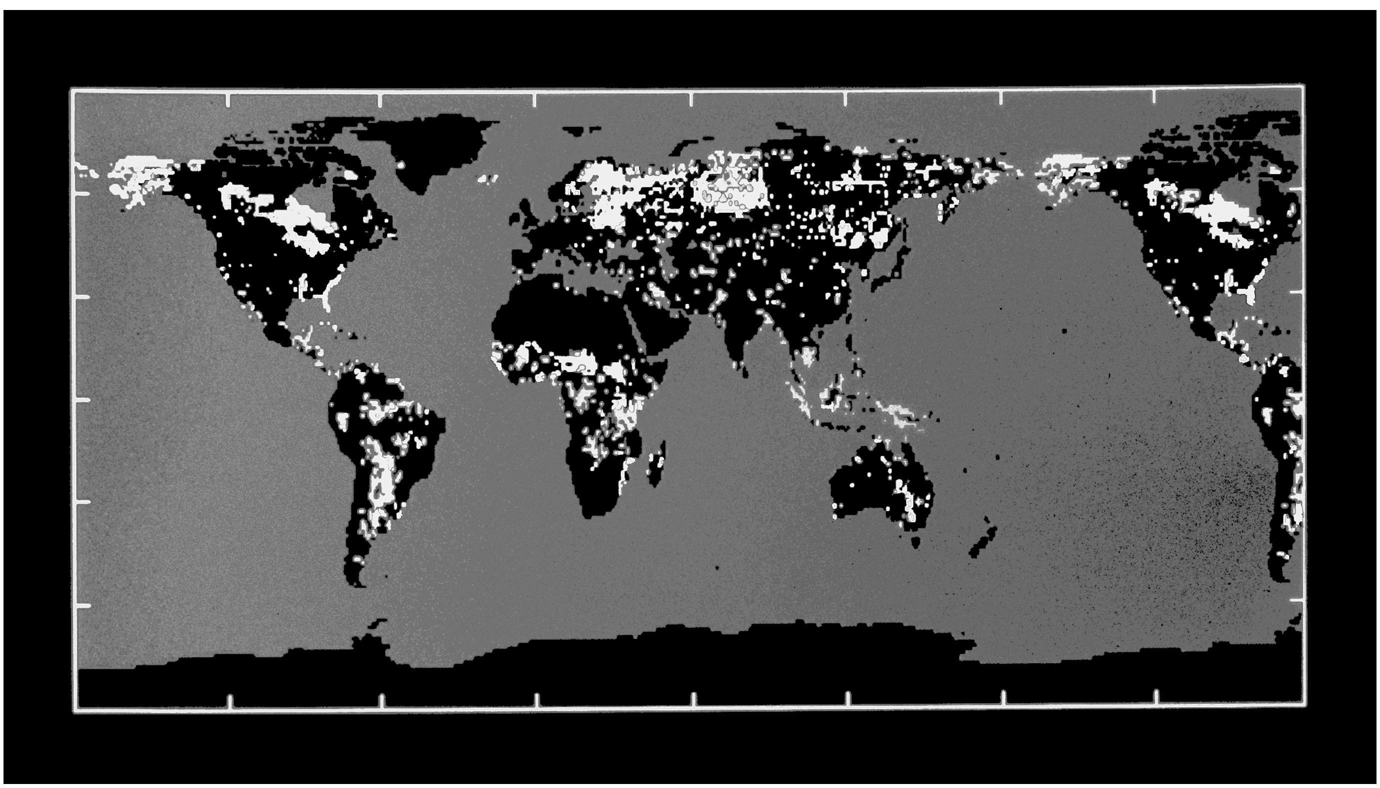

Figure 6-1: Global distribution of wetland ecosystems (modified after Matthews and Fung, 1987). Lighter areas denote wetlands.

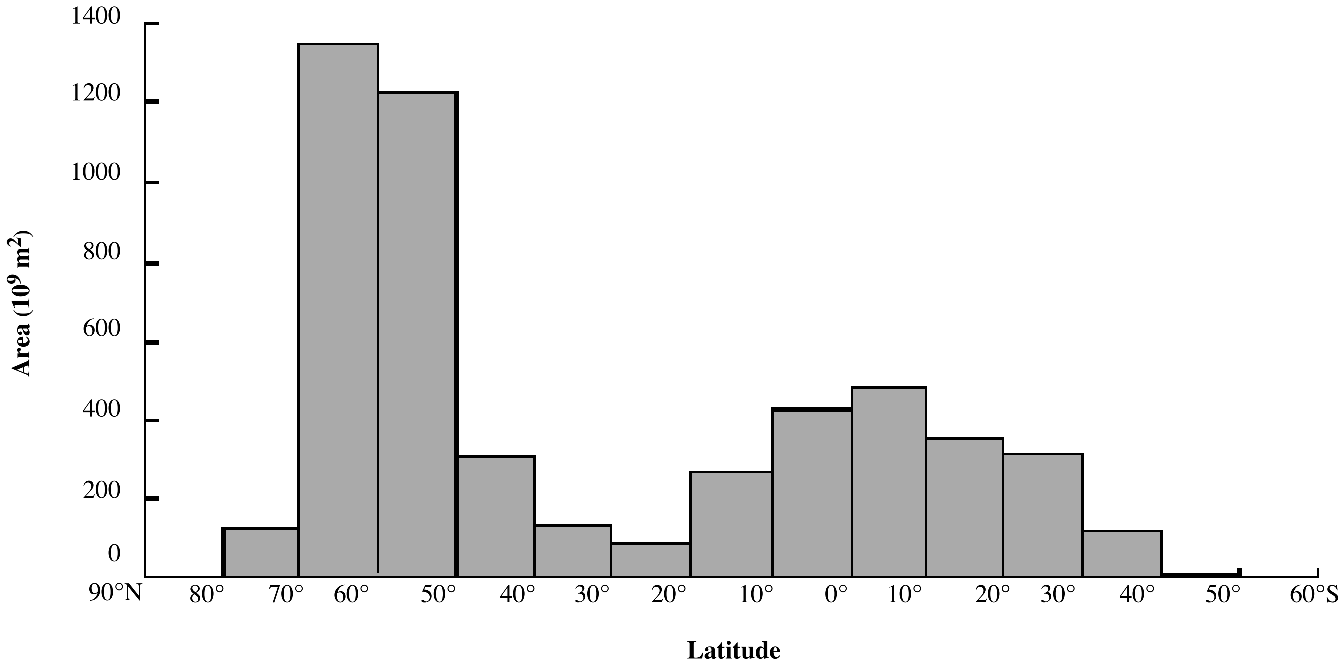

Figure 6-2: Distributions of wetland types along 10° latitudinal belts (modified after Matthews and Fung, 1987).

have the effect of replacing imported energy sources and reducing foreign-exchange requirements (Bord na Móna, 1985). However, large-scale harvesting of peat has led to the destruction of peatland ecosystems, and peat mining has the dual effect of removing a CO_2 sink (but a source of CH_4) and adding to the CO_2 in the atmosphere (see Rodhe and Svensson, 1995).

In the recent past, nonconsumptive benefits of wetlands such as recreation (Mercer, 1990), archaeology (Coles, 1990), education, and science usually were given lower priority in management plans than directly consumptive values because they are highly aesthetic and their values are difficult to quantify (Reimold and Hardinsky, 1979). However, these values have been given much greater attention in recent years, and wetlands worldwide are starting to be considered highly valuable areas to conserve.

6.2.1. Habitats and Diversity

The total biodiversity (flora and fauna) of wetlands generally is high in comparison with terrestrial ecosystems. Wetlands provide protective cover and essential feeding, breeding, and maturation areas for a wide range of invertebrates, as well as cold- and warm-blooded vertebrates (Gosselink and Maltby, 1990; Clark, 1979). Some animals are entirely dependent on wetland habitats; others are only partially so. In North America, for example, muskrats and beavers fall into the dependent group, whereas raccoons and various species of deer fall into the non-dependent one. In many areas, the remoteness and inaccessibility of wetlands has attracted species that may not be totally wetland dependent but take advantage of the protection and shelter they provide. For example, the Pantanal in Brazil, Paraguay, and Bolivia provides an important habitat for the jaguar (Dugan, 1993).

Probably the best known function of wetlands is as a provider of year-round habitats, breeding areas, and wintering sites for migratory birds, depending on their location (Bellrose and Trudeau, 1988; Dugan, 1993). One example is the prairie pothole region in the United States, where the value of the region as habitat for breeding birds, especially waterfowl, has been thoroughly documented. Annual production is correlated with the number of wet basins for many duck species (Boyd, 1981; Krapu *et al*., 1983; Reynolds, 1987). More than half of the waterfowl production in North America occurs within this region (Batt *et al*., 1989).

6.2.2. Biogeochemical Values

Wetlands play an important role in the global budgets of carbon (C) and the trace gases CH_4 and nitrous oxide (N_2O). Wetland soils represent a major pool of C that may respond dynamically to climate change (Woodwell *et al*., 1995). Boreal wetlands, which are extremely susceptible to climate change, are a major contributor to the global CH_4 budget (Matthews and Fung, 1987).

Wetlands are efficient in trapping pollution and processing wastes in human-dominated landscapes. Wetlands have been found to be important "sinks" for pollutants moving from upland areas, preventing their movement into surface water and groundwater (Mitsch and Gosselink, 1993); indeed, artificial

Table 6-1: *Causes of wetland losses (modified after Dugan, 1990).*

	Floodplains	Marshes	Peatlands	Swamps
Human Actions				
Drainage for agriculture, forestry, and mosquito control	++	++	++	++
Stream channelization for navigation and flood protection		+		
Filling for solid waste disposal, roads, etc.	++	++		
Conversion for aquaculture	+	+		
Construction of dikes, dams, and levees	++	++		
Discharge of toxic compounds and nutrients	++	++		
Mining for peat, coal, gravel phosphate, etc.	+		++	++
Groundwater abstraction	+	++		
Sediment diversion by dams, deep channels, etc.	++	++		
Hydrological alterations by canals, roads, etc.	++	++		
Subsidence due to extraction of groundwater, oil, gas, minerals, etc.	++	++		
Natural Causes				
Subsidence			+	+
Sea-level rise				++
Drought	++	++	+	+
Hurricanes and storms			+	+
Erosion	+		+	
Biotic effects	++	++		

Notes: ++ = common and important cause of wetland loss; + = present but not major cause of wetland loss.

Table 6-2: *Wetland values (modified after Dugan, 1990).*

	Floodplains	Marshes	Peatlands	Swamps
Function				
Groundwater recharge	++	++	+	+
Groundwater discharge	+	++	+	++
Flood control	++	++	+	++
Erosion control	+	++		
Sediment/toxicant retention	++	++	++	++
Nutrient retention	++	++	++	++
Biomass export	++	+		+
Storm protection	+			
Microclimate stabilization	+	+		+
Water transport	+			
Recreation/tourism	+	+	+	+
Products				
Forest resources	+			++
Wildlife resources	++	++	+	+
Fisheries	++	++		+
Forage resources	++	++		
Agricultural resources	++	+	+	
Water supply	+	+	+	+
Attributes				
Biological diversity	++	+	+	+
Uniqueness to culture	+	+	+	+

Notes: ++ = common and important value of that wetland type; + = less common and important value.

wetlands are being used to treat wastewater. Declines in these functions due to climate change could have important economic and aesthetic implications, particularly in heavily developed areas (Arheimer and Wittgren, 1994).

6.3. Sensitivities and Impacts

6.3.1. Which Wetlands are Most Vulnerable to Climate Change?

It is difficult to determine the vulnerability of specific types of non-tidal wetlands to climate change. One line of reasoning suggests that wetlands in naturally stressed environments appear to tolerate less additional stress than those located in favorable conditions (Lugo and Brown, 1984), meaning that they are more vulnerable to the alterations in hydrological regimes that are expected to result from climate change. By this reasoning, depressional wetlands (found in depressions in the landscape) with small watershed areas and situated in areas where the climate is either dry or wet at present will be most susceptible to these effects (Mitsch and Wu, 1995). In contrast, wetlands along floodplains and lakes should be able to adapt to a changing climate by migrating along river edges up- and downstream as well as up- and downslope to follow water—although the efficiency of such migration will be dependent on a number of factors, including catchment area, topography, and human settlements.

A second line of reasoning suggests that wetland types that have a large degree of inherent exposure to high spatial and temporal variation in environmental conditions may have a greater potential for adaptation to climate change (see Section 6.4).

Arctic and subarctic peatlands will be extremely vulnerable to climate change if warmer temperatures lead to a thawing of the permafrost layer and affect their hydrology through drainage or flooding (Gorham, 1994; Oechel and Vourlitis, 1994; OTA, 1993). These wetlands have a limited capacity to adapt to climate change because it is unlikely that new permafrost areas will form. In addition, non-tidal wetlands located near the coast are vulnerable to changes in climate due to sea-level rise, which would have severe impacts resulting from chemical and hydrological changes caused by intrusion of saline seawater (see Section 6.5.5).

6.3.2. Importance of Different Climate Variables

No single factor determines how climate change will affect individual wetland ecosystems. The variables that are predicted to change include temperature, precipitation, and CO_2 concentrations, resulting cumulatively in changes in water availability. Changes in the frequency and duration of flooding and drought and any alterations in disturbance regimes will be particularly important in determining how the ecological functions of wetlands ultimately are affected.

6.3.2.1. Temperature

Temperature is an important factor controlling many of the ecological and physical functions of wetlands. Primary productivity, microbial activity, and habitat are all controlled to a certain extent by temperature. Temperature also affects evapotranspiration rates, which has implications for the hydrological regime of wetlands by transporting water from the ecosystem to the atmosphere.

6.3.2.2. Precipitation

Precipitation regulates the direct inflow and amount of water to wetland ecosystems. However, the effect of a change in precipitation on a given wetland will depend on the type of wetland and the topographic and geographic characteristics of the region (drainage area, relief, and so forth). For example, very large wetlands, like the Okawango delta in Africa, are supplied with water from a considerable distance. In this case, the spatial variability of climate change could affect the balance between supply and evaporative demand. Further, in wetlands located along floodplains, a change in water availability throughout the drainage area or region will affect flooding and the hydrological regime in complex ways.

Poiani *et al.* (1995) show that the seasonality of precipitation changes is very important to wetland ecosystems. Climate change affecting spring precipitation and runoff may have the greatest impact on wetland hydrology and vegetation. Some modeling studies have indicated that there may be a threshold temperature beyond which changes in precipitation become less important to wetland hydrology. In one study, Poiani and Johnson (1993) conclude that precipitation changes are much less influential on hydrological regimes under a +4°C scenario than under a +2°C scenario.

6.3.2.3. CO_2 Concentration

Current research suggests that elevated CO_2 levels may have a direct fertilization effect on some types of vegetation, leading to higher production rates (Idso and Kimball, 1993). Elevated CO_2 concentrations seem to increase plant tolerance to stress, including photoinhibition, high or low temperature extremes, drought, and waterlogging (Hogan *et al.*, 1991). However, multi-species, intact ecosystems may show complex responses to an increase in CO_2 concentrations (Korner and Arnone, 1992). Elevated CO_2 concentrations in the atmosphere also may affect the rate of evapotranspiration through changes in water usage by plants (Bunce, 1992; Kimball and Idso, 1983). However, the effects of increased CO_2 on transpiration and water-use efficiency appear to decrease as water availability increases or as temperature decreases (Oechel and Strain, 1985). Any changes in transpiration may influence regional water balances and hydrological regimes because vegetation is a critical component of the cycling of water between soils and the atmosphere (Salati and Vose, 1984). Until detailed mechanistic questions regarding the biochemistry and physiology of wetland vegetation can be resolved, the extent to which wetlands will respond to increased CO_2 concentrations remains uncertain (Larson, 1994).

6.3.2.4. Extreme Events

Wetlands are sensitive to extreme climate events such as heavy spring flooding and summer drought (Gorham, 1991). Potential changes in precipitation patterns related to the amplitude, periodicity, or frequency of extreme events are critical components in modeling wetland responses to climate change (Poiani and Johnson, 1993). Extreme droughts make wetlands more sensitive to fire (see Sections 6.5.4 and 6.5.5; Gorham, 1994), which could impact ecological functions such as vegetation cover, habitat value, and carbon cycling. At the same time, such biomass burning is likely to result in massive emissions of smoke particles (aerosols) to the atmosphere, which may offset some warming, at least regionally (Penner *et al.*, 1992). Sea-level rise may affect some inland wetlands, causing saltwater intrusion that could result in an encroachment of salt-tolerant wetland communities.

6.3.2.5. Water Availability and Movement

Combined changes in temperature, evapotranspiration, precipitation, and CO_2 concentrations ultimately affect the hydrologic regime in a wetland ecosystem. It is critical to consider these combined effects because responses can be nonlinear. For example, it has been found that relatively small differences in precipitation can produce substantial differences in water level, especially for smaller temperature increases (Poiani and Johnson, 1993). Whereas decreased water availability will cause wetland loss due to concomitant drying, climate models suggest that some areas will become wetter—particularly high-latitudes in the winter. Although few studies have examined the potential impacts in these cases, it is conceivable that wetter conditions could be conducive to wetland development in areas not currently occupied by wetlands—as has occurred in areas of the Sahel (see Section 6.5.2).

In some cases, the movement of water in itself can benefit wetlands because it contributes to nutrient transport, aeration, and so forth, and because species can more readily distribute themselves according to the hydrological conditions to which they are adapted. Floods also create currents capable of exporting toxic compounds that otherwise could accumulate in sediments (Lugo *et al.*, 1990a). However, extremely intense hydrological fluxes tend to stress wetland ecosystems.

6.3.3. Effects on Wetlands Due to Climate Change

Climate changes affecting the areal extent, distribution, and hydrological regimes of wetlands are expected to have important effects on their ecological functions. These effects must be assessed in light of many uncertainties, particularly concerning the interactions of atmospheric water, surface water, and groundwater components of wetlands (Winter, 1988).

6.3.3.1. Areal Extent and Distribution

At present, regional scenarios do not provide adequate information to determine the direction or magnitude of change in the areal extent of wetlands (Gorham, 1991). It seems likely that some wetland regions will become moisture-limited, while other non-wetland areas will develop a climate conducive for wetland development. At this time, however, any estimation of the change in global areal extent would be very uncertain (see Gorham, 1991).

A few studies have attempted to estimate possible regional changes in wetland distribution, although they tend to involve areas that are projected to experience net losses in water availability rather than areas that are expected to experience increases. For example, a study by Brock and van Vierssen (1992) of hydrophyte-dominated wetlands in southern semi-arid regions of Europe concludes that an increase in temperature of 3–4°C would decrease the areal extent of habitat for hydrophytes by 70 to 85% within 5 years—suggesting that wetlands in other semi-arid and arid regions will be very sensitive to climate warming (see Section 6.5.2).

Poiani and Johnson (1993) conducted a study to understand how possible changes in the areal extent of a semipermanent wetland in the prairie pothole region of the United States might affect its ecological functions. For this study, they developed a simulation model for hydrological and vegetation responses. Using output from the Goddard Institute for Space Studies (GISS) general circulation model (GCM) for current and doubled-CO_2 climates (mean monthly air-temperature increase of 3 to 6°C and precipitation ranging from -17% to +29%) in an 11-year simulation, they project a 3% increase in the overall size of this wetland under current climate but a decrease of nearly 12% under the greenhouse scenario. Further, the areas of open water would decrease from 51% at the beginning of the simulation to 0% by the fourth year, allowing emergent plant species to spread over the entire wetland. This change would have serious implications for the wildlife in the region because these areas are extremely important breeding areas for waterfowl (see Section 6.2.1). This study indicates that even if the total decrease in wetland area due to a warmer climate is relatively small (12%), the overall change in wetland characteristics can have severe effects on many of the existing functions and values of wetlands. The model also indicates that wetland size, depth, and vegetative characteristics are more sensitive to changes in temperature than to either increases or decreases in precipitation.

Another study of the prairie pothole region (Larson, in press) examines the relationship between climate variables and the percentage of wet basins, using a multiple linear-regression model. This study focuses on closed-basin wetlands surrounded by either grassland or aspen parkland. The study found that when temperatures increase by 3°C in subsequent model runs

(15 years simulated), the Canadian and U.S. grassland models project declines in the percentage of wet basins of 15% and 28%, respectively. The aspen parkland model, however, projects a decline of 56% in the number of wet basins with increased temperatures. Model response to changes in precipitation were uniform and small across the region. An important consequence of geographical differences in wetland response to temperature is that as waterfowl extend their migrations farther north in drought years, they may face decreased probability of finding suitable wetlands.

A study by Zhang and Song (1993) examines the possible effects of climate change on the areal extent of the wetlands of eastern China, where 75% of the country's wetlands are located. The study examines climate change under six hypothetical climate scenarios (precipitation increasing or decreasing by 10% and temperature increasing 1, 2, and 3°C); the areal extent of herbaceous wetlands declines under all scenarios.

At high northern latitudes, warming could cause a poleward migration of the northern treeline. This shift would decrease the winter albedo because the tree canopy has much lower albedo than exposed snow surfaces (Bonan *et al*., 1992), greatly affecting regional climate by absorbing more of the sun's incoming energy.

Another implication for northern peatlands is the expected melting of permafrost due to higher temperatures (see Chapter 7). Harriss (1987) concludes that an increase in temperature of 2°C would shift the southern boundary of permafrost in the Northern Hemisphere to the north. The melting of permafrost is likely to have drastic effects on peatland hydrology and landscape patterns, leading to lowered water tables in some areas and flooded thaw lakes in others, as well as to thermokarst erosion (Billings, 1987; Gorham, 1991). It has been suggested (Zoltai and Wein, 1990) that such melting may shift bogs on permafrost back to fens, from which they originated after the warm mid-Holocene period. Vegetetation could shift from black spruce/Sphagnum/lichen (which are typical for bog ecoystems) to grasses, sedges, and reeds. Further, the rate of climate-change impacts on northern peatlands may be such that it causes degradation of southern regions much faster than the northern regions can expand northward (Gorham, 1991). These shifts also would have implications for the carbon cycle, as well as the flux of especially CH_4 from northern peatlands (see Section 6.5.3).

6.3.3.2. Functions

Functions are processes necessary for the self-maintenance of ecosystems, such as primary production, nutrient cycling and decomposition. Wetland functions can be categorized as biological, biogeochemical, or hydrological. These are distinct from, but often translate into, the socioeconomic values perceived by society (Brinson, 1993). None of these categories is exclusive, and each may influence the other; for example, any changes in wetland plant species have far-reaching effects on a wide range of wetland functions due to the unique structural, chemical, and ecological characteristics of different plants.

6.3.3.2.1. Biological functions

Biological functions relate to vegetation, habitats, and species diversity. Climate changes resulting in increased or decreased temperature and water availability will affect the composition and production of vegetation, the quality and areal extent of habitat available for species, and species composition and diversity (Thompson and Hamilton, 1983; Junk, 1983, 1993; Bradbury and Grace, 1983; Reader, 1978; Bernard and Gorham, 1978).

The species composition of plant communities in wetlands is critically affected by water movement and hydroperiod (Lugo *et al*., 1990a). Often, extended flooding and a longer hydroperiod will result in tree mortality and the replacement of forest by herbaceous vegetation (Lugo *et al*., 1990a). A long-term lowering of the water table would probably lead to similar changes in the composition and production of the vegetation as found in drainages made for forestry (e.g., in Sweden and Finland).

In forested wetlands subjected to drainage, the lowering of the water table has resulted in an increase in tree-stand volume (Keltikangas *et al*., 1986; Hånell, 1988). Based on data from several different wetland types given by Hånell (1988), Rodhe and Svensson (1995) calculate that the increase in tree-stand volume could range between 1.2–6.0 kg dry biomass/m^2. Similar results are reported in studies on wetlands in Finland (Ilvessalo and Ilvessalo, 1975).

Changes in wetland plant communities can have important effects on decomposition, nutrient cycling, and plant production functions. The nature and amount of plant litter production strongly influences wetland soil microbial populations (Melillo *et al*., 1982; McClaugherty *et al*., 1985; Bowden, 1987). Several studies have found strong links between wetland plant community types and microbial decomposition and nutrient-cycling processes in fens and bogs (Svensson, 1976, 1980; Svensson and Rosswall, 1984; Verhoeven *et al*., 1990; Verhoeven and Arts, 1992; van Vuuren *et al*., 1992, 1993; Koerselman *et al*., 1993). Microbial decomposition of litter and the release or "mineralization" of nutrients contained therein enhances plant productivity and litter quality (nutrient content, degradability; Pastor, 1984). Different plant communities demonstrate different rates of nitrogen availability to plants, carbon storage, and microbial processing of pollutants (Rosswall and Granhall, 1980; Pastor *et al*., 1984; Morris, 1991; Duncan and Groffman, 1994; Weisner *et al*., 1994; Schipper *et al*., 1994).

The physical and chemical characteristics of plants also strongly influence insect species and populations, which provide life-support functions for wetland-dependent birds, fish, and mammals (Mitsch and Gosselink, 1986; Kiviat, 1989). In conservation biology, there is intense interest in the effects of changes in plant species on the habitat value of wetlands (Bratton, 1982; Harty, 1986; Mooney and Drake, 1986; Center *et al*., 1991; McKnight, 1993).

6.3.3.2.2. Biogeochemical functions

Biogeochemical functions include pollution trapping and waste processing, carbon cycling (Svensson, 1986; Armentano and Menges, 1986; Silvola, 1986; Sjörs, 1980; Gorham, 1990, 1991; Miller *et al*., 1983; Marion and Oechel, 1993), and the flux of greenhouse gases (Svensson *et al*., 1975; Svensson, 1976; Aselmann and Crutzen, 1989; Matthews and Fung, 1987; Bartlett and Harriss, 1993; Matthews, 1993; Bartlett *et al*., 1989; Urban *et al*., 1988; Freeman *et al*., 1993; Martikainen *et al*., 1993; Pulliam, 1993).

Wetlands, and especially peatlands, play a significant role in the carbon cycle and presently are net sinks of carbon. A recent compilation of estimates of the amount of carbon held in soil as organic matter (Woodwell *et al*., 1995) gave a mean of 1,601 Gt, of which about 20% (412 Gt of C) is stored in peatlands. Estimated average accumulation rates for boreal and subarctic peatlands range from 0.05–0.11 Gt C/yr (Armentano and Menges, 1986; Silvola, 1986; Sjörs, 1980; Gorham, 1990, 1991; Miller *et al*., 1983; Marion and Oechel, 1993). However, some peats may have reached a balance between the degradation and addition rates of organic matter (Malmer, 1992; Warner *et al*., 1993).

Laboratory experiments and field studies have shown that lowering the water table by 20–30 cm could increase CO_2 fluxes from peat soil 1.5–2.5-fold (Silvola *et al*., 1985; Moore and Knowles, 1989). However, it seems that changes in the water table are more significant between 0–30 cm than between 30–60 cm (Silvola *et al*., 1985). Any lowering of the water table would mean, on the average, an extra carbon release of about 100–300 g C/m^2/yr. Further, an increase in temperature of 1–5°C in northern peatlands could decrease carbon accumulation by 10–60% due to enhanced microbial activity (see Section 6.5.3). Very little is known about peatlands in tropical regions, and there is some disagreement about whether tropical peatlands at present function as net carbon sinks or sources (Immirzi and Maltby, 1992; Sorensen, 1993; Sieffermann *et al*., 1988; see Section 6.5.4). They are, however, large carbon stores, and any significant changes in the degree of storage have implications for carbon cycling.

In the recent geologic past, the tundra was a sink of 0.1–0.3 Gt C/yr (Miller *et al*., 1983; Marion and Oechel, 1993). However, recent climatic warming in the arctic (see Lachenbruch and Marshall, 1986; Chapman and Walsh, 1993), coupled with the concomitant drying of the active layer and the lowering of the water table, has shifted areas of the arctic from sinks to sources of CO_2 (Oechel *et al*., 1993). For example, arctic areas that were sinks of 0.1 Gt C/yr now are sources of 0.1–0.6 Gt C/yr (Oechel *et al*., 1993; Zimov *et al*., 1993). This illustration of a response of a northern wetland to warming suggests a major change in ecosystem function that may be an early indication of global change in a natural ecosystem.

Although wetland vegetation fixes atmospheric CO_2, biogeochemical processes give rise to other greenhouse gases, such as CH_4. The estimated contribution of wetlands to the annual atmospheric CH_4 burden is 55–150 Mt/yr (Prather *et al*., 1994). However, the flux measurements on which these estimates are based are biased toward wetlands in northern North America and the Scandinavian countries (Bartlett and Harriss, 1993; Matthews, 1993). Climate change leading to an alteration in the degree of saturation and flooding of wetlands would affect both the magnitude and the timing of CH_4 emissions (see Section 6.5.3.2). Drying of northern wetlands could lead to declines in CH_4 emissions (Roulet *et al*., 1993; Martikainen *et al*., 1995). Although emissions of N_2O from wetlands usually are low (Urban *et al*., 1988; Freeman *et al*., 1993; Martikainen *et al*., 1995), a lowering of the water table could increase emissions.

Climate change also can affect the chemical properties of wetlands. Some non-tidal wetlands are saline due to the surplus of evapotranspiration over precipitation. If rates of evapotranspiration increase, there is a risk that more salts will accumulate in these wetlands, which could impair the value of wetlands due to the loss of intolerant species. Wetlands that are presently freshwater could become saline. However, in regions facing a decrease in evapotranspiration, the existing saline wetlands could gradually change as salinity decreases. This will affect the chemical properties of the wetlands—which, in turn, has consequences for biological and ecological characteristics, affecting vegetation, habitat value, and species composition (including the invertebrate community; Swanson *et al*., 1988).

An increase in temperature also will affect processes such as pollution trapping and waste processing because these processes are regulated by microbial activity and plant uptake, which are important sinks for nutrients (such as nitrogen and phosphorus) and various kinds of pollutants (heavy metals, pesticides and herbicides; Gilliam *et al*., 1988; van der Valk *et al*., 1979; Brinson, 1990; Brix and Schierup, 1989; Johnston, 1991; Mitsch and Gosselink, 1993). However, the key features to which these water-quality functions are connected are coupled to the water regimes of wetlands (Kadlec, 1989), so it is impossible to make any general statements about the impact of climate change on these functions.

6.3.3.2.3. Hydrological functions

Hydrological functions include flood control (Andriesse, 1988; Novitzki, 1979; Boelter, 1966; Gosselink and Maltby, 1990) and aquifer recharge (Bernaldez *et al*., 1993). Wetlands temporarily store runoff water, thereby reducing floodwater peaks and protecting downstream areas (Andriesse, 1988; Novitzki, 1979; Boelter, 1966; Gosselink and Maltby, 1990). A reduction of wetland area due to climate change could severely hamper flood-control efforts in some regions. Under certain conditions, climate change could enhance recharge to major aquifers by overlying wetlands—particularly in arid or semi-arid regions, where groundwater is of considerable importance as a source for public water supply and irrigation (Bernaldez *et al*., 1993; see Section 6.5.2). The contribution of wetlands to groundwater resources depends on the detention of water within the wetland during dry periods; this is likely to be reduced by loss of wetlands (Bernaldez *et al*., 1993).

At northern latitudes, projected higher spring and winter temperatures would likely affect the amount and timing of runoff from snowmelt and rainfall by changing the patterns of soil freezing and thawing (Mimikou *et al*., 1991). It also would decrease the ratio of snow to rain, leading to additional changes in spring snowmelt (Cohen, 1986; Gleick, 1987; Croley, 1990).

6.3.4. Interactions Between Climate Change and Other Wetland Stressors

The impacts of climate change on wetlands will interact with other anthropogenic stresses. Due to the importance of hydrological regime and wetland response, we confine ourselves to discussing the cumulative impacts of hydrological changes in wetlands. Apart from climate change, the most common disturbances to the hydrological regimes of wetland ecosystems are alterations in plant communities, storage of surface water, road construction, drainage of surface water and soil water, alteration of ground water recharge and discharge areas, and pumping of ground water. All of the anthropogenic activities and natural causes mentioned in Table 6-1 will, to various extents, impact the hydrology of wetlands. Drainage for agriculture, for example, would cause drastic changes in water level and means near-total destruction of wetland ecosystems, whereas construction of dams for water management could be less severe if efforts to maintain waterflow through the subjected wetlands are made. Due to site-specific responses by wetland ecosystems and the large range of plausible anthropogenic and natural stressors, a quantitative evaluation of them in combination with climate change is difficult. It is conceivable, however, that within the next decades the main threat to wetlands is likely to be due to anthropogenic activities rather than climate change.

6.4. Response Options—Adaptation, Conservation, and Restoration

The prospects for adaptation, conservation, and restoration of wetland ecosystems in response to climate change varies with wetland type and the specific wetland function being considered. For wetland functions that are an aggregated product of regional or global wetland resources (e.g., trace-gas fluxes, carbon storage), there are no human responses that can be applied at the necessary scale. Moreover, changes in these functions as wetlands adapt to climate change are difficult to predict due to the site-specific nature of wetland responses to climate change. For wetland functions that are more local in scale (e.g., habitat value and pollutant absorption), prospects for adaptation, conservation, and restoration are better than for large-scale functions. However, these prospects will vary strongly with wetland type. Some wetland types have a higher potential for adaptation to climate change due to their inherent exposure to high spatial and temporal variation in environmental conditions. For example, the prairie pothole wetlands discussed in Section 6.3.3.1 respond dynamically and naturally to wide variation in seasonal and annual climate (van der Valk and Davis, 1978; Poiani and Johnson, 1989).

Other wetland types—for example, boreal peatlands—have high spatial variability in plant communities caused by variation in macro- and microtopography (Sjörs, 1950). Hotter, drier, and/or wetter climates will result in a change in the wetland community in these wetlands, but the natural spatial and temporal variation inherent in these systems suggests that the changed community will resemble at least some component of the existing community (Poiani and Johnson, 1989).

Given the site-specific nature of wetland responses to climate change and the importance of inherent variation in fostering potential for adaptation, wetland conservation and restoration efforts should focus on preserving this variation (McNeely, 1990; Leemans and Halpin, 1992; Peters and Lovejoy, 1992). Wetland restoration and creation technologies have a great potential for ameliorating the effects of climate change on wetland functions. However, wetland ecology is complex, and the enthusiasm for wetland creation and restoration has outpaced the scientific understanding and technological development needed to successfully create wetlands for specific purposes (Reed and Brown, 1992; van der Valk and Jolly, 1992). Key areas of concern in wetland creation are how to establish a persistent and resilient assemblage of desired wetland plants, and a lack of understanding of the relationships between different plant assemblages and a range of wetland functions—from microbial pollutant-attenuation mechanisms to sequestration of soil carbon to food-chain support (Zedler and Weller, 1990; Pickett and Parker, 1994).

6.5. Examples and Case Studies

6.5.1. Introduction

This section uses case studies from certain defined wetland areas and regions to demonstrate climate-change impacts on different wetland types and geographic locations. The areas selected for these studies are the Sahel region of Africa, northern wetlands, the Kalimantan of Indonesia, and the Florida Everglades of the United States. These different locations will provide insight into the uses and responses of peatlands, marshes, and floodplains, as well as measures that are presently being taken in some places to restore wetlands affected by human uses and alterations.

The purpose of the case studies is to illustrate the general concepts described in this chapter through specific examples and to identify factors that make wetlands more or less vulnerable to any possible changes. The case studies also illustrate the type of information needed for any given location in order to conduct an assessment of potential risks, as well as the specificity of the information that may be gleaned about possible impacts at this time at individual sites.

Most of the case studies deal with the local functions, uses, and benefits of the wetlands and how these will be affected by climate change: These wetlands are valuable to nearby populations as sources of water, as agricultural land, as habitat for species, and for their other hydrological functions. Some of the case studies deal with the biogeochemical functions of wetlands and the ways in which human alterations and climate-change impacts on wetlands could affect the cycling of CO_2, CH_4, and N_2O to the atmosphere, which would result in global-warming feedback.

6.5.2. *Case Study: The Sahel*

6.5.2.1. Background

The Sahelian wetlands are dynamic ecosystems (see Box 6-1). During the past 2 decades, new wetlands of up to 1,800 hectares have formed, while other wetlands have been degraded (Piaton and Puech, 1992; Brouwer and Mullié, 1994a). Wetlands in the Sahel include the floodplains of the large rivers and Lake Chad, as well as thousands of small permanent and temporary wetland ecosystems scattered throughout the region (see Sally *et al*., 1994; Brouwer and Mullié, 1994a; Windmeijer and Andriesse, 1993). Some of these wetlands, such as the small valley bottoms, contain water only during runoff events.

The small wetlands in the Sahel are very important for agriculture (MHE-DFPP, 1991; MHE-Niger, 1991a; Brouwer and Mullié, 1994b) and are used for dry-season cropping, using moisture left in the soil after the floods have receded, or for small-scale irrigation. In the period 1984–91, between 42,000 and 64,000 hectares of wetlands were used each year in Niger for dry-season cropping, generating an annual income of \$200–\$4,300 per hectare (MAE-Niger, 1993; Raverdeau, 1991; Cherefou Mahatan, 1994). In 1990, $4.1x10^6$ hectares of dryland cropping (mostly millet) in Niger generated an income of about \$70 per hectare. This difference in income per hectare is in part a reflection of the quality of the food produced. The small wetlands also have greater production of fish per hectare and greater density of birds than the large wetlands (Brouwer and Mullié, 1994b; Mullié and Brouwer, 1994).

6.5.2.2. Societal Context

The human carrying capacity of the Sahel region is already matched or exceeded by population density (van der Graaf and Breman, 1993); dryland agriculture or large-scale migration to other parts of the region are unlikely to be able to relieve the situation. As a result, wetlands will be more sought-after, and pressure for conversion of wetlands to rice fields should increase due to increasing urbanization in West Africa and its effects on the demand for rice.

Droughts also tend to increase pressure on wetlands because they affect the migration patterns of people in the area. During the severe droughts of 1975 to 1988, the number of villages on the Nigerian section of Lake Chad increased from 40 to more than 100 (Hutchinson *et al*., 1992). Similarly, the use of the Hadejia-Nguru wetlands in Nigeria for agriculture has increased due to droughts. This increase was not foreseen when plans were made for the construction of dams and irrigation projects in the catchment upstream. Wet periods have traditionally meant migration to the normally drier and less-populated northern and western parts of the Département Tahoua, Niger. Because these people often stayed despite less-abundant

Box 6-1. The Wetlands of the Sahel: Effects on Agriculture, Habitat, and Hydrology

Background: The wetlands of the Sahel region of Africa consist of the floodplains of major lakes and rivers, as well as thousands of smaller wetland ecosystems scattered throughout the region. These smaller wetlands are particularly important for agriculture and as a source of income from agriculture; floodplains are important for their hydrological functions. The wetlands in the Sahel are already expected to come under increased pressure for conversion to agriculture and other uses due to urbanization and population growth projected over the next decades.

Possible impacts: With the possible exceptions of eastern Niger and Chad, climate change is expected to decrease the extent of wetlands in the Sahel, due to changes in temperature and precipitation projected by current scenarios. These changes are likely to result in a net loss of water in most of the large rivers in the Sahel over the next 30–60 years, with the exception of the major rivers flowing into Lake Chad. Although few studies exist on the effects on species, the loss of wetlands due to climate change could create a risk of extinction for some local populations of turtles and birds.

Conclusion: Although climate change could have some beneficial effects on the wetland regions of the Sahel, there would be many adverse impacts; some could be potentially irreversible. Even if the predicted decrease in rainfall in the western Sahel were followed by a recovery to present levels or more, part of the damage that is likely to occur in the interim would be very difficult to repair.

rainfall, they increased the pressure on natural resources, including wetlands (DDE-Tahoua, 1993).

6.5.2.3. Climate Change Expected

Rainfall in the Sahel region is greater in the north than in the south (see Nicholson, 1978, 1994; Hutchinson *et al*., 1992). This analysis focuses on the wet season (June–August), when most dryland crops are grown. According to the IPCC Working Group II scenarios (Greco *et al*., 1994), precipitation in the Sahel zone is projected to decrease by 2020 in the Senegal to Burkina area and increase moderately to considerably in Niger and Chad. Temperature is projected to increase by 0.5–1.5 (0–2.0)°C. For the decade around the year 2050, the three models show less agreement overall, although all indicate that eastern Niger is likely to receive more rain. Temperatures would be similar to those around the year 2020, though possibly somewhat higher in the area of the headwaters of the Senegal and Niger rivers. In the headwaters of the Komadougou Yobé river, rainfall around the year 2020 is expected to be somewhat less than at present. For the year 2050, the scenarios are less conclusive: In the area of the headwaters of the major rivers flowing into Lake Chad, rainfall around 2020 and 2050 is expected to be moderately to considerably greater than now.

6.5.2.4. Effects on Water Availability and Vegetation

Overall, these changes suggest that there will be less water in most of the large rivers in the Sahel over the next 30–60 years, with the exception of the major rivers flowing into Lake Chad. This will mean less water available in the floodplains along these rivers, unless there are changes to the management of outflow from dams. Changes to the hydrology of the small wetlands will depend not only on climate change but also on whether they are supplied with surface water or groundwater, on the reaction of the natural vegetation, and on the extent of cropping in their catchment areas.

Recharge to shallow, unconfined groundwater could either increase or decrease as a result of climate change. The groundwater level in southwest Niger increased in the last decade (Leduc *et al*., in press; Bromley *et al*., in press a), either as a recovery from the droughts of 1983–84 and/or 1973–74 or as a response to changes in land use. Annual recharge under millet in southwest Niger is on the order of 1–200 mm, a factor ten times greater than under bush and older fallow vegetation (Gaze *et al*., in press; Bromley *et al*., in press b). Therefore, an increase in the area sown for millet—as noted by Reenberg (1994) and others—could result in a higher recharge to unconfined groundwater and the wetlands fed by such groundwaters.

The dryland areas should experience less evaporative water loss because less rainfall, at least initially, means less perennial vegetation. However, there will be increased runoff until a new vegetative cover is established. This increase in runoff will likely result in increased erosion (see van Molle and van Ghelue, 1991) and a faster silting up of wetlands. It also could create entirely new wetlands.

Higher temperatures also may adversely affect seedling emergence of millet, the staple cereal over much of the Sahel (see Monteith, 1981)—meaning that less millet would be harvested in the dryland areas and increasing the pressure on wetlands. However, during dry years in eastern Niger, infiltration into the heavier soils in depressions may be so low that cropping becomes unattractive (Reenberg, 1994). During dry years, water is more limiting than nutrients, and cropping on less-fertile upland soils with higher infiltration rates may become more attractive.

Desertification upon drought may result in a loss of wetlands due to moving sands (DDE-Tahoua, 1993; Mahamane Alio and Abdou Halikou, 1993; Framine, 1994). In part, this response can be related to the greater vulnerability of perennial vegetation to desiccation under a monomodal semi-arid rainfall regime (Ellis and Galvin, 1994), when topsoil and seedbanks are washed or blown away during the drought. Droughts may make wetland vegetation more vulnerable to fires intended to improve rangeland vegetation (Hutchinson *et al*., 1992).

6.5.2.5. Effects on Biodiversity

There are few assessments of how these changes could affect local biodiversity. Mullié and Brouwer (1994), following Gibbs (1993), suggest that small wetlands in the Sahel are important for the metapopulation dynamics of certain taxa—meaning that the loss of small wetlands may lead to a significant risk of extinction for local populations of turtles and small birds (Gibbs, 1993). Taxa that are easily transported by wind or birds as adults, eggs, cysts, larvae, and so forth would be subject to less risk (Dumont, 1992; Mullié and Brouwer, 1994; Magadza, 1994).

The importance of wetlands to birds in semi-arid areas can vary greatly from year to year depending on local and regional rainfall (Rose and Scott, 1994). If wetlands in the western Sahel become drier, relatively mobile birds dependent upon wetland habitats will move into wetlands further east (i.e., Niger, northern Nigeria and Cameroon, Chad).

6.5.3. Northern Wetlands: Effects on the Carbon Cycle and Trace-Gas Emissions

6.5.3.1. Peat Accumulation

Peatlands are a major store of organic carbon and contain approximately 20% of the total amount of organic carbon stored in soils (see Section 6.3.3.2). A majority of this is in the Northern Hemisphere as carbon stored in the form of peat (see Box 6-2). Peat formation and accumulation in these wetlands is influenced by climate change: A change in climate would lead to changes in the flux of carbon (CO_2 and CH_4) between these ecosystems and the atmosphere, generating a feedback on climate warming.

Box 6-2. Northern Wetlands: Effects on the Carbon Cycle and Trace-Gas Emissions

Background: Peatlands are a major store of organic carbon and contain approximately 20% of the total amount of organic carbon stored in soils. The northern peatlands account for a majority of this as carbon is stored in the form of peat. This case study demonstrates how changes in climate may affect the flux of carbon (CO_2 and CH_4) and nitrous oxide between these ecosystems and the atmosphere, generating a feedback on climate warming.

Possible impacts: Current scenarios suggest that climate change is likely to increase the flux of CO_2 to the atmosphere because temperatures influence whether carbon litter is accumulated into the peat profile or oxidized. In addition, the position of the water table regulates the extent of oxygen penetration into the peat profile. This means that drainage will cause increased decomposition, leading to increased fluxes of CO_2 to the atmosphere, although this effect will decline over time. Further, a decrease in water availability could lead to a decrease in CH_4 emissions from wetlands. Changes in variables such as the areal extent of wetlands and the duration of the active period will determine whether there will be a change in the total CH_4 flux from a wetland. A lowering of the water table would probably not affect nitrous oxide emissions from bogs but could lead to an increase of emissions from fens, although emissions of nitrous oxide from wetlands tend to be low.

Conclusion: Changes in the source/sink relationship have already occurred in wetlands in some parts of the world. Both climate change and human (non-climate) factors are likely to further affect the biogeochemical functions of wetlands.

Wetland vegetation fixes CO_2 from the atmosphere and eventually is added to the top layers of the wetland soil as organic litter. Part of the organic litter is oxidized and emitted as CO_2, and some is accumulated as peat. Several investigations have shown that soil CO_2 efflux from peatlands is strongly related to temperature (Svensson *et al*., 1975; Svensson, 1980; Glenn *et al*., 1993; Crill, 1991), although Moore (1986) found a poor correlation between temperature and CO_2 emission rates. Since most of the CO_2 emitted is produced by the upper soil layers (Stewart and Wheatly, 1990), it mainly originates from organic material that has not yet become a part of the peat proper, known as the catotelm. Carbon litter reaching the soil may be either oxidized (emitted as CO_2) or accumulated. Thus, a change in CO_2 emissions will be directly correlated to the portion of organic matter transferred to the catotelm. Because the CH_4 formed will be accompanied by a nearly equal amount of CO_2 (see Gujer and Zehnder, 1978), this relation should hold for most peatland types.

According to one CO_2 efflux temperature-moisture regression model (Svensson, 1980) of the transfer rate of organic matter to the catotelm due to changes in temperature, CO_2 emissions should rise by 12% for each degree Celsius increase in average temperature, given the mean seasonal moisture level. Accordingly, a temperature increase of 1–5°C would result in a 10–60% decrease in the rate at which organic matter is transferred to the catotelm.

Peat accumulation has varied substantially over past millennia (see Malmer, 1992), which is reflected in the quality of peat as a substrate for decomposers. The degradation rate of deep peat is limited by substrate quality rather than by abiotic factors (Hogg *et al*., 1992). Therefore, the decomposition rate in deep peat will be fairly constant and only marginally affected by changes in temperature. Such constancy would improve the usefulness of the model described above in predicting changes in peat accumulation in response to a temperature change. Changes in hydrology also will influence the accumulation rate of peat because the position of the water table regulates the extent of oxygen penetration into the peat profile. The effect of a lowered water table due to climate change can be compared to the effects noted after drainage of peatlands for forest production. Drainage results in an increased decomposition rate and elevated fluxes of CO_2 to the atmosphere (Silvola *et al*., 1985; Silvola, 1986; Moore and Knowles, 1989): A 25-cm lowering of the water table gave rise to a twofold increase in CO_2 emissions from peat (Silvola *et al*., 1985; Moore and Knowles, 1989). Depending on the type of peatland, this elevated flux may reduce carbon accumulation or even reverse the net flux of carbon to make the peatland a net source of atmospheric CO_2. Drained minerotrophic forested peatlands have been reported to respond in the latter way, whereas nutrient-poor peatlands may continue to accumulate carbon at a predrainage level (Laine *et al*., 1994; see also Tamm, 1951, 1965). Average CO_2 evolution from northern peatlands has been estimated at about 200 gC/m^2/yr (Silvola *et al*., 1985; Moore 1986, 1989). Following drainage, an elevated CO_2 flow will decline over time (see Armentano and Menges, 1986) owing to substrate depletion as the more easily decomposable fractions of the peat become depleted. However, a drier climate will continue to "drain" the peat successively for a long period; the decline will occur later. To estimate the importance of this, it is assumed that the drainage response reported by Silvola *et al*. (1985) is linear with depth. The increase in CO_2 flows at subsequent drawdowns of 5 cm would then be 40 gC/m^2/yr or another 20% per depth interval.

The scenarios for 2020 and 2050 for the areas of boreal and subarctic peatlands project a temperature increase of 1–2°C and a decrease in soil moisture. Based on this temperature change, it seems reasonable to expect a 25% decrease in the addition of organic matter to the catotelm. It is assumed that this effect would be amplified in response to a decrease in soil moisture. Thus, it is conceivable that the peat accumulation rate will decrease to half of the present rate or even less (i.e., <0.025–0.055 Gt C/yr). Boreal peatlands may even become net sources of atmospheric CO_2. In concluding his discussion of the response of northern wetlands to predicted climate change, Gorham (1991) gives the extreme example of a 1-cm breakdown of the boreal peat layers worldwide. This would result in 2 Gt C/yr, which corresponds to more than a third of the present release of carbon to the atmosphere via fossil fuel combustion. The response in net primary production in relation to climate change is more difficult to predict and may enhance or reduce the effects caused by the estimated changes in the degradation features of peatlands (see Malmer, 1992).

6.5.3.2. Climatic Controls on Methane Flux

The net emission of CH_4 from peatlands is dependent on how much CH_4 is formed in the anaerobic parts of the profile and the amount oxidized in the oxic zones. Because the position of the water table and the associated capillary fringe determine the thickness of the zones of production and oxidation of CH_4, the flux of CH_4 is intimately tied to the surface hydrology of the wetland—which in turn is controlled by climate (precipitation and evaporation) and the topographic and geologic setting (surface and subsurface water flow). A decrease in water availability in the peat can lead to a decrease in CH_4 emissions (Whalen *et al*., 1996; Sundh *et al*., 1994a, 1994b; Martikainen *et al*., 1995; Roulet *et al*., 1993). Deeper penetration of oxygen into the peat also will enhance the capacity of the peat to act as a CH_4-oxidizing filter for CH_4 diffusing from the CH_4-forming sources below. Changes in the direction or magnitude of any or all of the controlling variables discussed above will affect the CH_4 flux. A change in the total CH_4 flux from northern wetlands can be expected if the areal extent of wetlands changes, the duration of the active period changes, and/or the per-unit-area production or oxidation of CH_4 changes.

The relations among moisture content, temperature, and CH_4 flux in individual wetlands have received much attention (Bartlett *et al*., 1992; Crill *et al*., 1988; Dise *et al*., 1992; Moore and Knowles, 1989; Moore and Dalva, 1993; Moore and Roulet, 1993; Svensson, 1976; Svensson and Rosswall, 1984). These relations have been used to estimate qualitatively the year-to-year variation in the flux and the possible direction of change based on changes in temperature and precipitation obtained in 2 x CO_2 scenarios (Table 6-3). Four different approaches have been used to address this issue: (1) correlation of the time series of CH_4 fluxes with the time series of temperature and moisture using interannual data sets; (2) direct observations of changes in CH_4 flux in manipulation experiments that simulate expected changes in wetlands due to climate change; (3) modeling of variability of CH_4 flux using existing climate records and regressions between temperature and CH_4 flux; and (4) modeling of thermal and hydrological regimes of wetlands in 2 x CO_2 climate scenarios and then modeling of change in CH_4 flux using regressions relating CH_4 flux to temperature and moisture in order to predict a change in flux. These studies have shown that the flux of CH_4 is moderately sensitive to changes in temperature and very sensitive to changes in moisture. Using these relative sensitivities as a guide, a qualitative assessment of CH_4 flux from northern wetlands according to six possible climate scenarios is made (Table 6-3). At present, it is not possible to obtain reliable quantitative estimates of the change in flux because the surface hydrology of general circulation models is too coarse to adequately represent the small changes in moisture regime that probably affect the CH_4 flux.

6.5.3.3. Effects on Nitrous Oxide Emissions

Emissions of N_2O from northern wetlands are low. *In situ* chamber measurements and laboratory experiments with intact peat cores have revealed emissions below 0.025 g N_2O-N/m²/yr (Urban *et al*., 1988; Freeman *et al*., 1993; Martikainen *et al*., 1993). A lowering of the water table of bogs will not affect their N_2O emissions, whereas it could strongly increase emissions from fens. Annual emission rates in the range of 0.05–0.14 g N_2O-N/m²/yr have been reported for drained peat by Martikainen *et al*. (1993) and Freeman *et al*. (1993). The difference between bogs and fens can be explained partly by the fact that drained peat profiles of fens have the capacity to nitrify (Lång *et al*., 1994). N_2O emissions from drained boreal fens are lower than those from drained agricultural organic soils but 10–100 times higher than the rates from coniferous forest soils (Martikainen *et al*., 1993).

6.5.4. Case Study: Kalimantan

6.5.4.1. Background

Kalimantan is one of the largest islands (539,460 km²) in the Indonesian archipelago (see Box 6-3). The region has a humid tropical climate, with high temperatures and high precipitation. The peatlands of Kalimantan probably play a major role in determining local climate at the present time, although there is no substantial evidence to confirm this.

The largest wetland areas are found in low-lying alluvial plains and basins and flat-bottomed valleys. Most of the freshwater wetlands in the area are forested swamps, specifically either freshwater swamp forests or peat swamp forests (Silvius, 1989). The freshwater swamp forests are rich in epiphytes, rattans, and palms. They provide shelter for a range of rare and endangered species of wildlife, including numerous bird species. The peat swamp forests are a further developmental stage of the freshwater swamp forest. Deep peats are found in the central and western parts of the island (Sieffermann *et al*., 1988, 1992; Rielly *et al*., 1992). The peat swamp forests have a relatively high diversity of tree species, but the variety of wildlife tends to be poorer than in freshwater swamp forests (Whitten *et al*., 1987). Because of the high acidity of the peats and the fact that they are difficult to drain, peat swamp forests are of limited agricultural value (Silvius, 1989). Both swamp types are important watershed areas capable of absorbing and storing excess water and reducing flooding in adjacent areas. They also are an important forestry resource, with many commercially valuable timber species.

The wetlands of Kalimantan currently are deteriorating through the loss of the natural ecosystem, including primary forest cover. Deforestation, drainage, and agriculture all limit the buffering capacity of developed wetlands, causing changes that are long-term and irreversible. Because much of the human settlement at the present time is located in the coastal zone, peat swamp forest on the deeper interior peats has not been subject to large-scale harvesting. These areas are used mainly for timber extraction rather than agriculture; hence, their vegetation cover remains relatively unmodified.

6.5.4.2. *Effects of Temperature Change*

The projected climate change for the region involves an increase in temperature ranging from 0–1.5°C. The effects of

Table 6-3: *Potential changes in CH_4 flux from northern wetlands due to changes in the thermal and moisture regime (adapted with additions from Matthews, 1993).*

Study Description and Location	Change in Thermal and/or Moisture Regime	Observed or Modeled Change in CH_4 Flux	Relative Sensitivity
Field observations of CH_4 flux and temperatures among tundra wetlands of the North Slope (Alaska) with differing moisture levels (1987–1989)[1]	$\Delta T = +4°C$ $\Delta T = +4°C$; wetter $\Delta T = +4°C$; drier	Four-fold increase Four- to five-fold increase Two-fold increase	Large positive sensitivity to temperature increase; small positive sensitivity to moisture change
Field observations of CH_4 flux from permanent tundra wetland sites (Alaska)[2]	4-year variation in temperature and moisture	4 times variation in flux: Flux increased with warmer, wetter conditions	Large positive sensitivity to both temperature and moisture changes
Field observations of CH_4 flux from drained boreal wetlands (Canada)[3]	$\Delta WT = -10$ cm $\Delta WT > -10$ cm	Elimination of CH_4 flux Wetland became small CH_4 sink	Large positive sensitivity to moisture change
Field observations of CH_4 flux from drained boreal wetlands (Finland)[4]	$\Delta WT = -4$ cm $\Delta WT = -20$ cm	Five-fold decrease Elimination of CH_4 flux	Large positive sensitivity to moisture change
Modeling study based on 20th-century historical summer temperature anomalies for five high-latitude wetland regions and a temperature/CH_4 flux regression model[5]	$\Delta T = \pm 2°C$	±15% variance in flux	Moderate sensitivity to temperature
Modeling study simulating change in summer temperature and water table for a northern fen (Canada) in a 2 x CO_2 scenario (+3°C, +1 mm/d P) and temperature/CH_4 flux, and water table/CH_4 flux regression models[6]	$\Delta T \approx +0.8°C$ $\Delta T = +2°C$ $\Delta WT = -14$ cm	+5% increase +15% increase -80% decrease	Moderate sensitivity to temperature; large sensitivity to moisture

Notes: ΔT = change in temperature; ΔWT = change in water table; P = precipitation.
[1]Livingston and Morrissey, 1991.
[2]Whalen and Reeburgh, 1992.
[3]Roulet *et al*., 1993.
[4]Martikainen *et al*., 1992.
[5]Harriss and Frolking, 1992.
[6]Roulet *et al*., 1992.

Box 6-3. The Forested Swamps of Kalimantan: Effects on Habitat, Hydrology, and Carbon Cycling

Background: The wetlands of Kalimantan are found in low-lying alluvial plains and basins and flat-bottomed valleys. Most of the freshwater wetlands in the region are classified as forested swamps, specifically as either freshwater swamp forests or peat swamp forests. The freshwater swamp forests are important in providing shelter for rare and endangered species; both types are important as watersheds and habitats for valuable tree species. They also are carbon sinks but release carbon into the atmosphere when water declines. The Kalimantan wetlands currently are stressed by the loss of the natural ecosystem through deforestation, drainage, and agriculture. These activities limit the buffering capacity of developed wetlands, causing changes that tend to be long-term and irreversible. However, these inland wetlands have escaped some interference because most of the human settlements are located along the coastal zones.

Possible impacts: Increased temperatures are likely to result in a longer period of reduced rainfall because higher temperatures will cause evapotranspiration to exceed precipitation. This is likely to have deleterious effects on the vegetation and hydrology of these wetlands. Climate change also could enhance peat losses in the region that currently result from human interference. On the other hand, increased precipitation in the dry season is likely to be beneficial, as the lower water levels that are typical in this season lead to a net loss of carbon into the atmosphere and an increased risk of fire (one of the greatest threats to their functioning).

Conclusion: It is possible that some measures may be taken in this region in the near future to abate the detrimental impacts caused by human (non-climate) stresses on these wetlands. The extent to which adaptations will be sufficient to counteract changes imposed by a changing climate as well cannot be determined. However, human activities that reduce the resiliency of these wetlands, as well as planned development of previously undisturbed areas of swamp forest, will likely lead to considerably enhanced carbon transfer from the wetlands to the atmosphere, even without climate change.

higher temperature and longer dry periods combine to produce a longer period when evapotranspiration exceeds rainfall and effective rainfall is greatly reduced. This, linked to increasing human activity on peatlands—such as timber extraction, agricultural development, and construction work—could have serious consequences.

Much of the Kalimantan lowland area is subjected to a distinct dry season from July to September or October in which there are high water losses from wetlands as a result of direct evaporation and evapotranspiration. Thus, water levels drop and peat oxidation occurs, with a net loss of carbon to the atmosphere. The spread of fire is one of the greatest threats to the functioning of these wetlands. Peat fires occur frequently in the region, creating palls of smoke sufficiently heavy to close local airports. In 1983–84, fires destroyed 3.5 Mha of both dipterocarp and peat swamp forest in Kalimantan, resulting in a direct economic cost of $2–12 million and an incalculable ecological cost (Maltby, 1986). The risk of fires spreading from cultivated to forest areas increases during the dry season and would increase if the dry season were extended.

6.5.4.3. Effects of Precipitation Change

Estimated precipitation changes for the area range from -20% during winter to +40% during the summer. The higher "summer" (i.e., dry-season) values are beneficial to the peatlands because this is the time when they experience the greatest drawdown of the water table. A decrease of precipitation in the wet season could be significant if, as a result, the dry season is extended.

Large-scale removal of the forests and drainage of the underlying peats could prevent further peat formation. The high peats of Kalimantan already appear to be degrading (Sieffermann *et al.*, 1988) and losing carbon directly through oxidation to the atmosphere or indirectly in surface drainage waters, followed by oxidation of carbon compounds at a later stage. Climate change would most surely exacerbate this degradation, leading to peat losses in this region.

6.5.4.4. Remediation Possibilities

A forest-management project in Kalimantan currently being sponsored by the British Overseas Development Administration will include suggestions for the sustainable management of the peat swamp forests. The resulting guidelines should help preserve the forest cover on the deeper peats, particularly if extraction methods do not intensify. Indonesian authorities also are introducing stricter regulations and controls on unnatural fires resulting from illegal land clearance and settlement. However, in 1986–89, a feasibility study was carried out to investigate the potential of using deep peat to generate electricity.

The extent to which these potential management changes will be sufficient to counteract the effects of climate change cannot be determined. However, utilization of the forests on these peats and planned development of previously undisturbed areas will likely lead to considerably larger carbon transfer from wetlands to the atmosphere even without climate change.

6.5.5. Case Study: The Florida Everglades

6.5.5.1. Background

The Everglades is a 500,000-hectare freshwater peatland dominated by vast expanses of sedge and sawgrass, interspersed with shallow-water aquatic communities (sloughs), wet prairies, and tree islands (Loveless, 1959; Gunderson, 1994). Peat accumulation and the subsequent formation of the Everglades began approximately 5,000 years ago as sea-level rise slowed after an initial rapid rise during deglaciation (Gleason and Stone, 1994). As recently as a century ago, the Everglades encompassed more than 1,000,000 hectares, but drainage for agriculture and urban development has resulted in the loss of more than half of the ecosystem (Kushlan, 1989; Davis *et al*., 1994). The remaining area has been dramatically altered by construction of impoundments, canals, levees, and water-control structures; the system is managed, primarily, as a water source (Light and Dineen, 1994). During the wet season (June–November), excess water from agricultural land and suburban areas is pumped into the Everglades; during the dry season (December–May), the Everglades serves as a water source (DeGrove, 1984). In addition, approximately 50% of the water from the Kissimmee River/Lake Okeechobee complex—the "headwaters" of the Everglades—is diverted by canals to the Atlantic Ocean and the Gulf of Mexico before recharging the wetland (Light and Dineen, 1994). Thus, the present-day Everglades is characterized by a general reduction in the hydroperiod (Fennema *et al*., 1994; Stephens, 1984; SFWMD, 1992; Walters *et al*., 1992).

Long-term rates of peat accretion in the Everglades average 0.8–2.0 mm/yr, based on ^{14}C dating of the basal peat (McDowell *et al*., 1969) and ^{210}Pb dating of peat cores (Craft and Richardson, 1993). However, alterations of the natural hydroperiod and nutrient regimes in the Everglades have resulted in changes in the rate of peat accretion. Areas experiencing reduced hydrology (caused by overdrainage) exhibit lower rates of accretion (1.6–2.0 mm/yr) compared to areas of extended hydroperiod (2.8–3.2 mm/yr) (Craft and Richardson, 1993). Likewise, pollen analysis of peat cores indicates a decrease in the extent of wetland vegetation such as sawgrass and slough and a concurrent increase in terrestrial "weedy" species (ragweed and pigweed) since drainage activities were initiated (Bartow *et al*., 1994). Thus, future changes in the Everglades ecosystem caused by global warming must be interpreted in the context of recent anthropogenic alterations of hydrology and nutrient regimes (see Box 6-4).

6.5.5.2. Effects of Sea-Level Rise

The most immediate effect of climate change will be accelerated sea-level rise, resulting in saltwater intrusion into the lower part of the glades from Florida Bay (Wanless *et al*., 1994). Increased salinity would result in encroachment of salt-tolerant wetland communities such as mangroves and salt marshes. The areal extent of freshwater communities such as sawgrass, slough, and wet prairie will decrease, and the amount of organic carbon sequestered also will decrease. Another biogeochemical consequence of saltwater intrusion is a shift in anaerobic decomposition away from methanogenesis toward nitrate and sulfate reduction.

6.5.5.3. Effects of Temperature Change

Temperature is expected to increase from 0.5 to1.5°C, likely resulting in an increase in evapotranspiration—which may

Box 6-4. The Florida Everglades: Effects on Water Supply and Critical Habitats

Background: The Everglades is a freshwater peatland dominated by sedge and sawgrass, with sloughs, wet prairies, and tree islands. The Everglades is important as a habitat for wildlife, fish, and plant species and as a water source for the neighboring community. It is estimated that drainage for agriculture and urban development in the past century has resulted in a loss of more than half of the ecosystem, and the remaining wetlands have been altered by other construction and so forth.

Possible impacts: Sea-level rise is expected to be perhaps the most important variable that will affect the Everglades, causing saltwater intrusion that is likely to result in an encroachment of salt-tolerant wetland communities. This would decrease the areal extent of the freshwater wetlands, with some effects on anaerobic decomposition. The increased evapotranspiration expected in some seasons would exacerbate this saltwater intrusion. Increased temperature is likely to cause a northward migration of some introduced species but could be conducive for other species. Climate change also is expected to affect the hydrology of the wetlands, causing higher water levels in the winter and lower levels in the summer. This could result in the loss of critical habitats such as sawgrass and wet prairie communities, although these losses are likely to be offset by an increase in woody shrubs and trees.

Conclusion: Overall, the impacts that are projected as a result of climate change would adversely affect the end-users of the ecosystem: waterfowl, fish, and other wildlife; hunters, fishers, and tourists; and surrounding populations that rely upon the Everglades for freshwater resources. However, some action is currently underway to modify the water-control structure in an effort to restore the Everglades.

further exacerbate saltwater intrusion into the Everglades. Although more water will be lost to evapotranspiration, it is likely that oxidation and subsidence of the peat soils will not be dramatically affected because rising sea level will augment the groundwater table, particularly in the southern Everglades. Another consequence of increased temperature may be the northward migration of introduced species such as *Melaleuca quinquenervia*. *Melaleuca,* which has overtaken large areas of the southern Everglades, is seemingly kept in check by frost (Bodle *et al*., 1994). However, increased temperatures caused by climate change might enable *Melaleuca* to colonize large areas of the northern Everglades.

6.5.5.4. Effects of Precipitation Change

Precipitation is projected to decrease during summer (0–20%) and increase during winter (0–20%). The winter months correspond to the dry season (November–May), when approximately 25% (10–15 inches) of the 50 to 60 inches of annual rainfall occurs (MacVicar and Lin, 1984). It is likely that an increase in rainfall during this season will reduce the rate of drawdown that normally occurs during this time. The reduction in summer rainfall in the wet season (May–October) should result in a lowering of the water table compared to current levels. These combined seasonal changes in rainfall should dampen the oscillations between the summer wet season and the winter dry season. As a result, water levels in the Everglades probably will be somewhat higher in the winter and somewhat lower in the summer than they are at present.

A dampening of the annual hydroperiod fluctuation may result in a decrease in the extent of sawgrass, the dominant plant community in the Everglades. Sawgrass communities are partly maintained by fire (Gunderson, 1994); increased rainfall during the dry season may reduce the frequency of fires—in particular, the severe fires that occur in the beginning of the wet season (May) that often burn large areas of the Everglades (Gunderson and Snyder, 1994). It is likely that wet prairie communities also will decrease in extent. These communities, which are important foraging habitat for wading birds (Hoffman *et al*., 1994), frequently dry down during the spring (Goodrick, 1984). The dampening of the annual hydroperiod fluctuations caused by global warming will likely result in the loss of much of this critical habitat. The decline of sawgrass and wet prairie communities probably will be offset by an increase in woody shrubs and trees. These species are not generally fire-tolerant and often compete more effectively against emergents when water levels are stable.

6.5.5.5. Socioeconomic Consequences

It is likely that the greatest impact of climate change will be the loss of freshwater resources that sustain the burgeoning human population of south Florida, as well as the unique Everglades wetland. Competition for this diminishing resource will surely result in a no-win situation for humans and the Everglades under a scenario of global warming and rising sea level.

On a positive note, the U.S. Army Corps of Engineers, which oversees the water resources of south Florida, is evaluating modifications to the system of impoundments, canals, levees, and water-control structures in order to restore the Everglades (and other south Florida ecosystems) while providing for other water-related needs in the region (U.S. ACOE, 1994). This ambitious project, which could cost upward of $2 billion, is designed to increase the spatial extent of wetlands and restore the hydrology and water-quality conditions of the Everglades and other south Florida ecosystems.

6.6. Future Research Needs

Wetlands are highly valued in many areas. The lack of data to fully address their responses to climate change calls for several areas of research in the future:

- Site-specific responses are variable. There is a strong need for a local and regional coupling of climate-change predictions with known responses of specific wetlands, which would allow for modeling of the necessary interactive responses of the hydroperiod, temperature, and water availability at these scales. A network of different wetland sites in different regions of the globe should be established to form the base for such research.
- The feedback on climate by changes in trace-gas flows from wetlands, especially CO_2 and CH_4, upon a climate change calls for a strengthening of ongoing research in this field. This will aid in the judgments necessary for the introduction of adaptation and remediation measures on wetlands.
- The vast "grey" literature existing on different wetland subjects within the frames of local, regional, and country research reports should be examined to further substantiate site-specific responses by different wetlands, including changes in species composition, biogeochemistry, and socioeconomic consequences.

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